PROGRESS IN MODELING ELECTRON CLOUD EFFECTS IN HIF*

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ABSTRACT

Stray electrons can arise in positive-charge accelerators for heavy ion fusion (or other applications) from ionization of gas (ambient or released from walls), or via secondary emission. Their accumulation is affected by the beam potential and duration, and the accelerating and confining fields. We present electron orbit simulations which show the resultant e-cloud distribution; ion simulations with prescribed e-clouds which show the effect on ion beam quality; a gyro-averaged model for including electron dynamics in ion simulations, and its implementation status; and progress in merging the capabilities of WARP (3-D PIC code for HIF) (D.P. Grote, A. Friedman, I. Haber, Proc. 1996 Comp. Accel. Physics Conf., AIP Proc. 391), 51 (1996), with those of POSINST (e-clouds in high-energy accelerators) (M.A. Furman, LBNL-41482/CBP Note 247/LHC Project Report 180, May 20, 1998).

OUTLINE

- Review: why we care about stray electrons
- A plan for self-consistent modeling
- Results from steps in this plan:
  - Electron clouds from secondary electrons produced by calculated ion scrapeoff
  - Ion simulations with specified electron clouds
- Options for simultaneous treatment of electrons and ions
- Summary

Related papers:

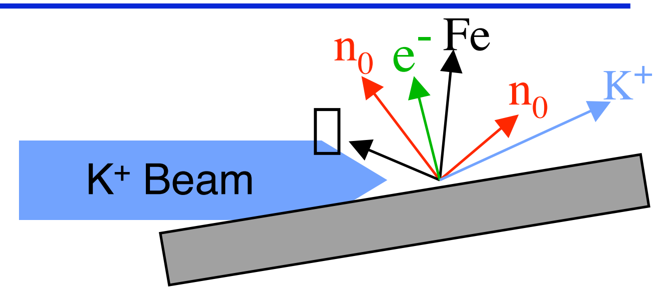
RP1.077, Molvik et al (poster, this session)

RP1.080, Stoltz et al (poster, this session)

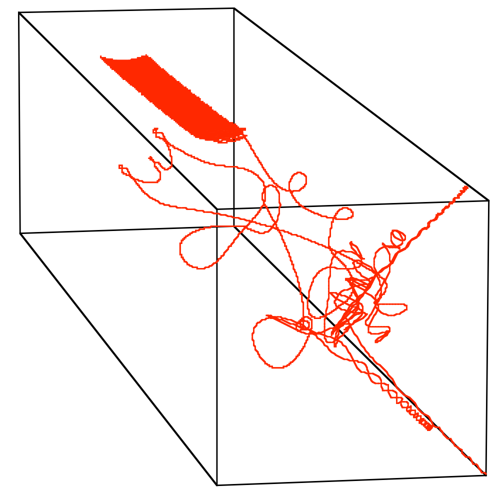
STRAY ELECTRONS ARE A CONCERN

- Electron clouds recognized problem in positive-charged-particle accelerators (*e.g.* 27 papers at May ’03 Particle Accelerator Conference)
- Potential issues for ion beam:
  - Growth of emittance (focus problems)
  - Growth of envelope, possibly hitting wall (loss of current, further-enhanced source of electrons)
  - Drive for instability (two-stream, …)
- Distinguishing aspects of HIF accelerators (U.S. main line with magnetic quadrupole focusing):
  - Linac with high line charge density
  - Long pulse time ~ 1 μs
  - Induction accelerator --
    - hard to clean beam pipe large neutral emission coefficient at pipe wall (> 10^3)
    - Beam pipe only in quad magnets scrape-off only in quads
  - Economic mandate to maximally fill beam pipe
  - Large fraction of length occupied by quads (>50% at injector end)

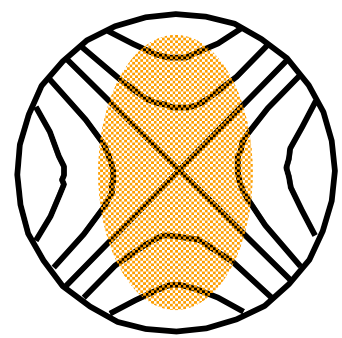
Electrons from gas released at walls in quads dominate



- Because of above, e^- from ionization of neutrals released from walls dominates for long (multi-μs) pulses.
  – Born trapped by beam potential, mainly in quads
    - Bounce radially
    - Drift axially
    - Acquire enough energy in gap to escape
    - Hence τ_e ~ time to drift through 1 quad



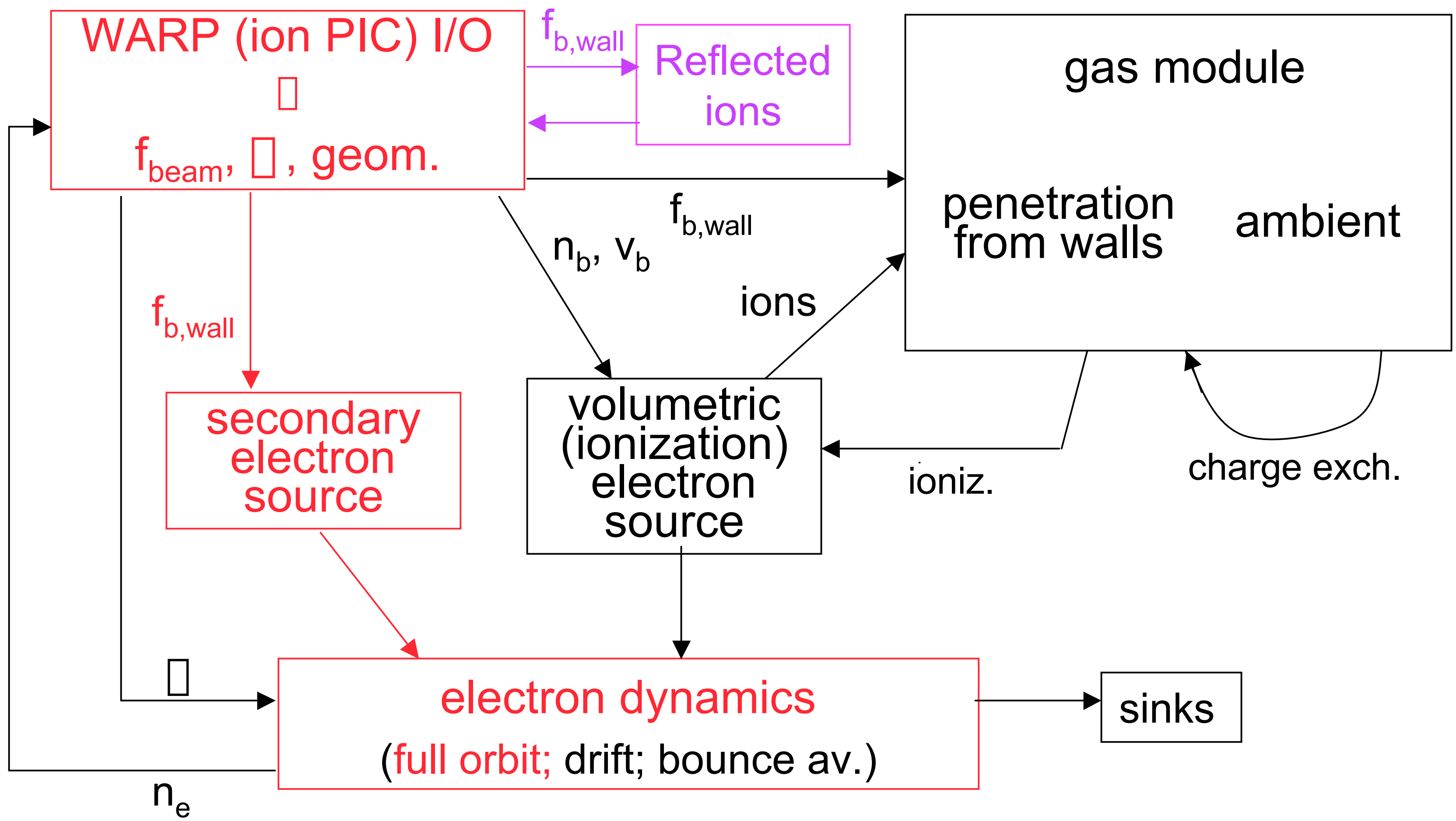
- For shorter pulses: secondary electrons from ion bombardment
  – Nominal lifetime 1 transit during beam flattop
  – For small fraction born on field lines that penetrate deep into interior, collisionless pitch-angle scattering (nonadiabaticity) can make lifetime much longer



- n_e predominantly in quads

Toward a self-consistent model of electron effects

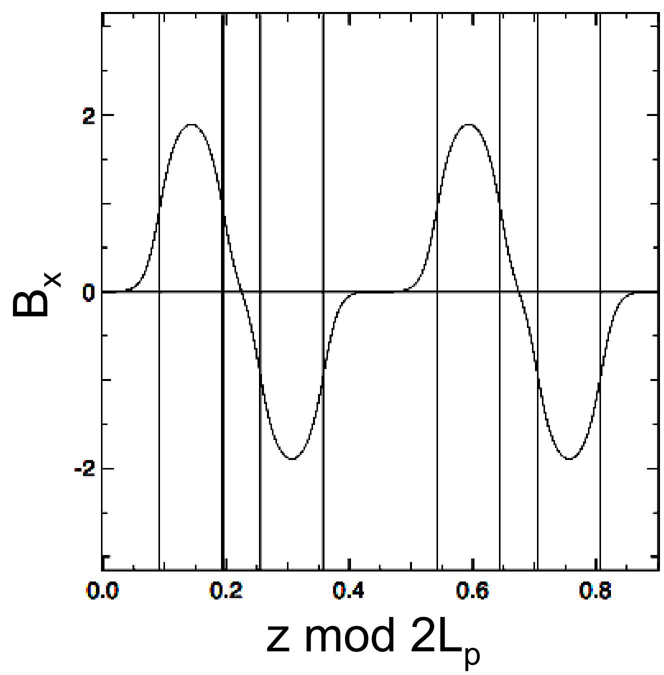
- Plan for self-consistent electron physics modules for WARP



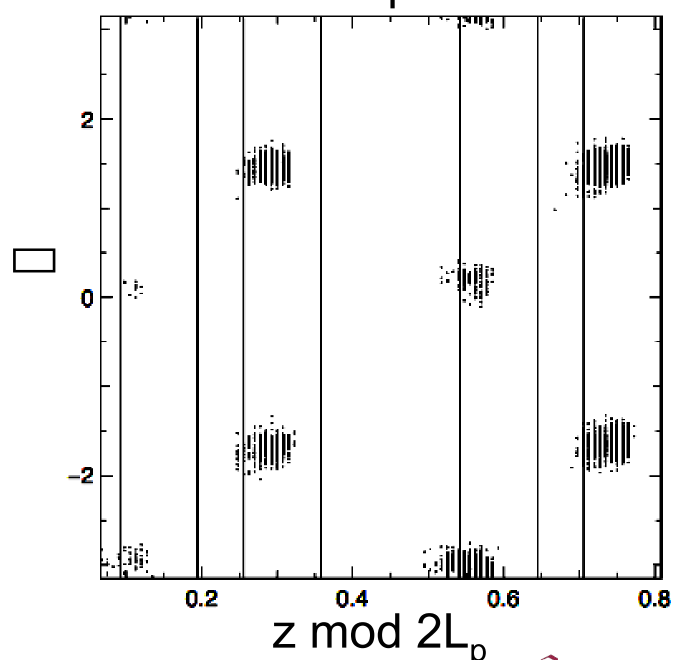
- First step: Runs with modules indicated in red + approx to magenta

Calculation of n_e from secondary-electron sources

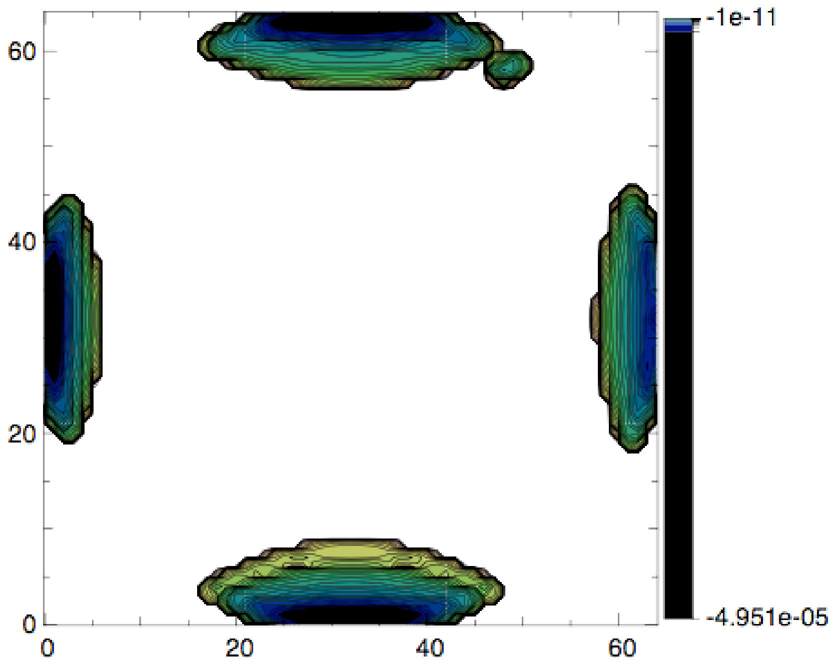
- Find lost ions from WARP slice simulation (HCX-like design quads, syncopated lattice; no ion scattering)
- Calculate SEY based on fit to experimental results (see RP1.077): SEY ~ min(6/cos , 130)
- Follow full electron dynamics with WARP (until lost or max 4000 timesteps)
- Accumulate electron density.

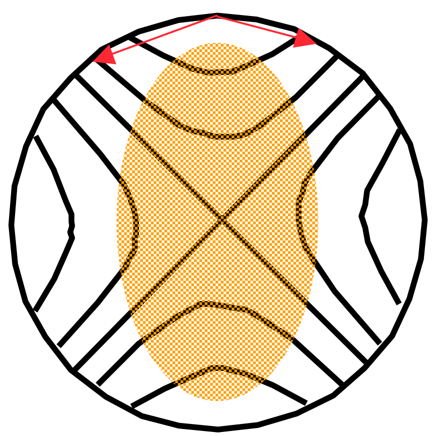


Ion loss positions



Resultant ecloud:



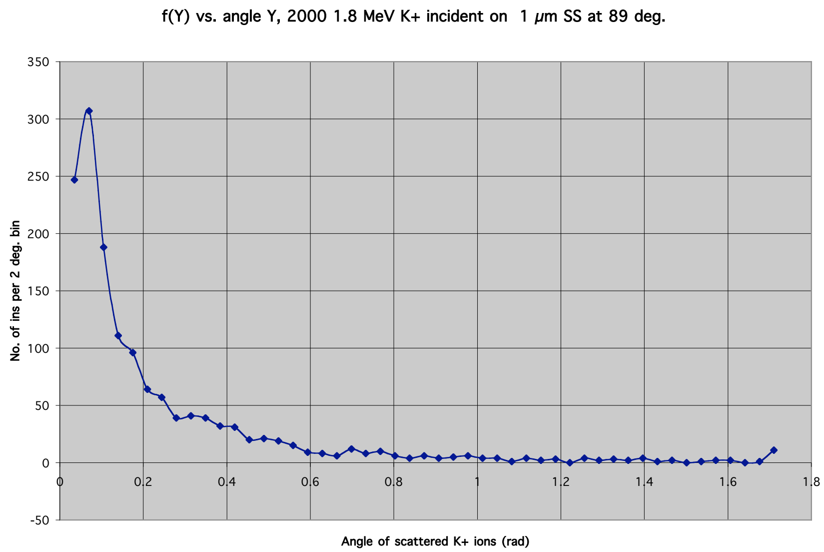


- Result, electron cloud confined close to electron birth positions, due to non-penetrating field lines.
- Illustrates need to treat scattered ions
  - TRIM MC calcs indicate most ions scatter at walls
  - Scatterred ions can reach field lines that reach deeper into beam.

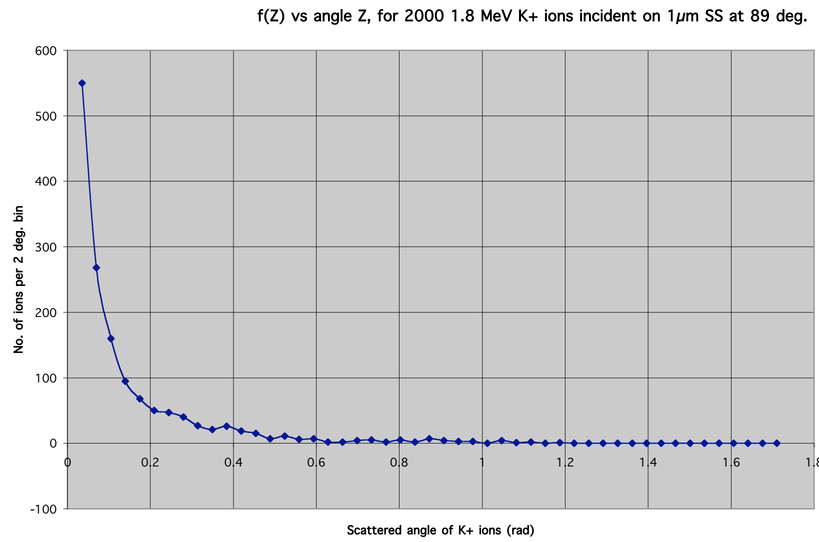
Ecloud with scattered ions

- Crude model of scattered ions
  - Straight-line orbits
  - Weights approximately fit TRIM statistics
  - Follow only single generation of scattered ions

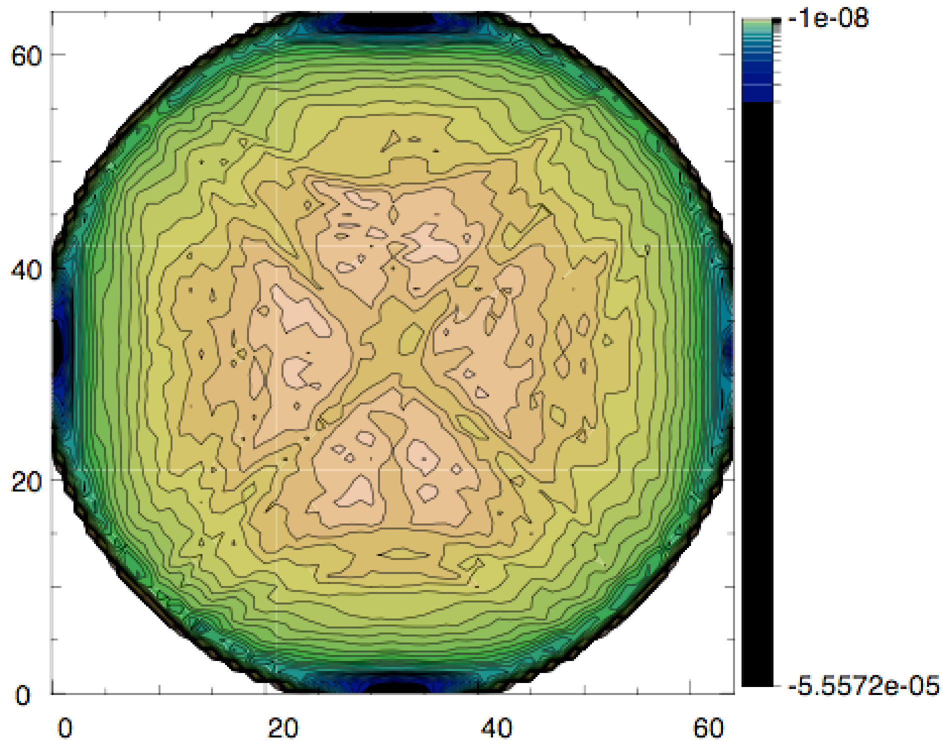
TRIM: scattering vs angle from beam prop direction



TRIM: scattering vs angle from normal transv. to beam



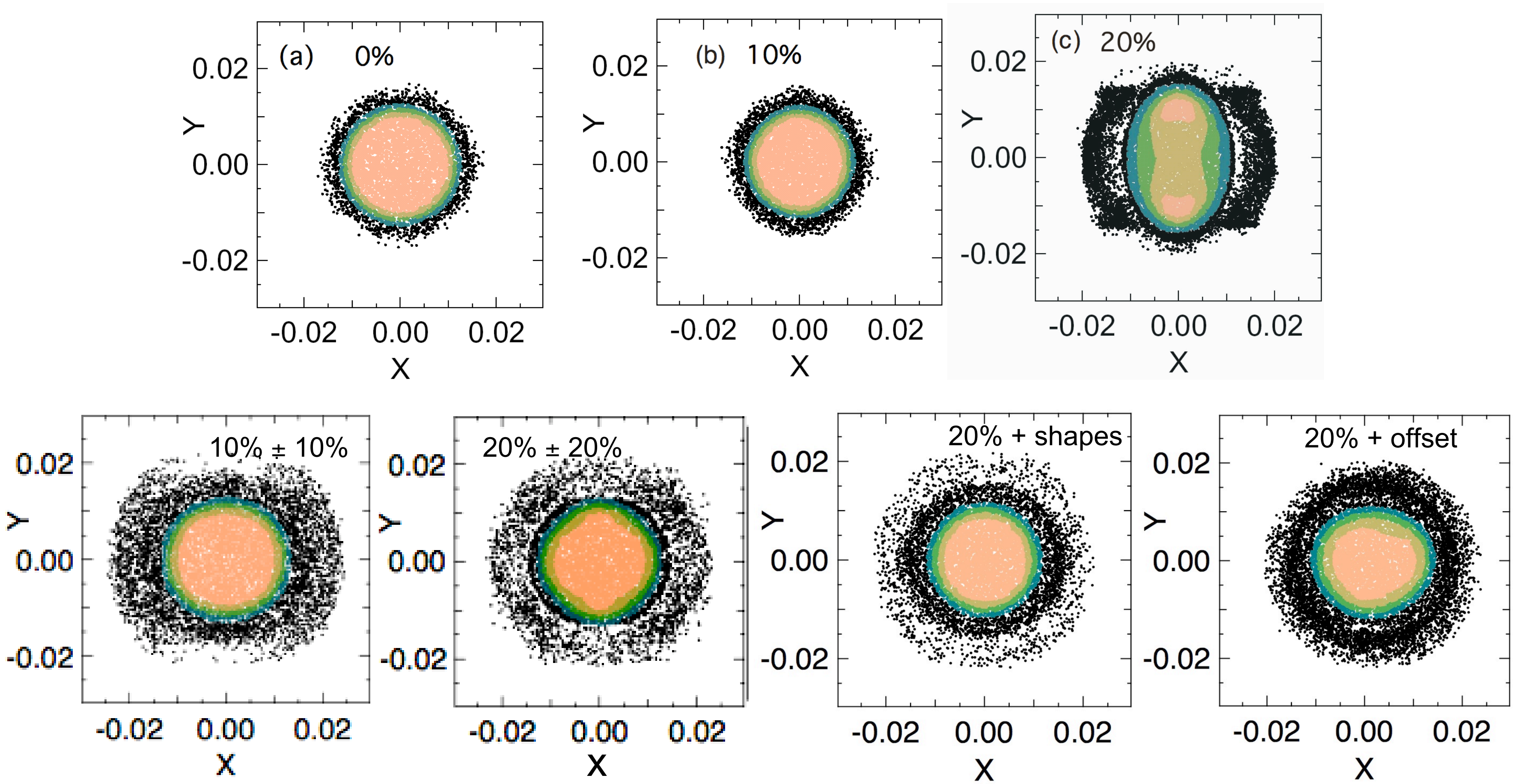
Resulting electron cloud is quite different…



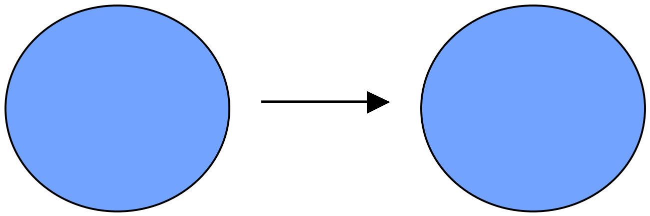
- Observation: small tail reaching more penetrating field lines makes big difference
- Relatively high density along diagonals as expected for nonadiabatic trapping
- To do: orbits for electrons from ionization of gas

Electron effects on ions: random variations

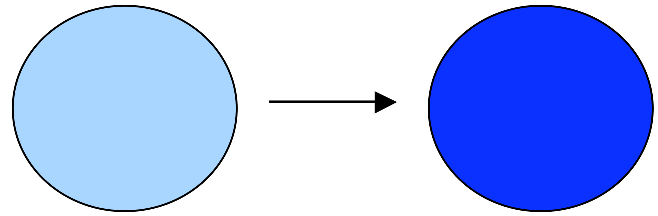
- Perform ion simulations with legislated negative charge distributions to mock up electrons (neglects e-i collective effects)
  - Const n_e
  - Random n_e amplitude variations (const in quad), 100% max modulation
  - Considered also random offsets, random radial shapes-- smaller effects



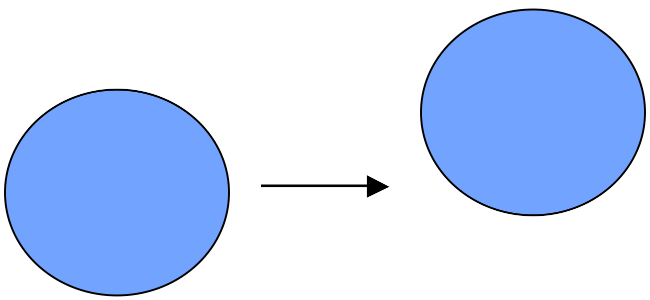
Types of ecloud perturbations



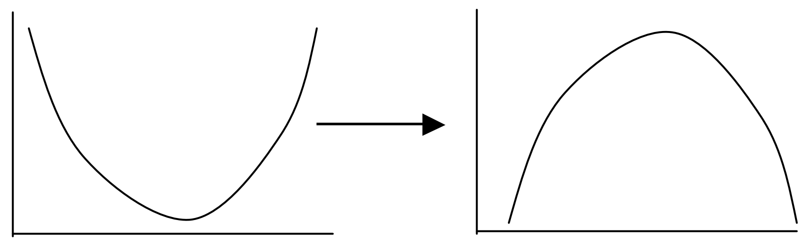
uniform



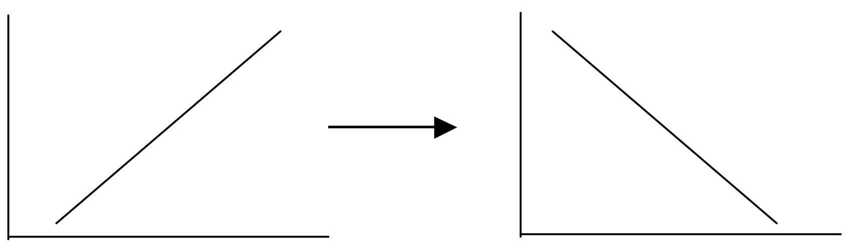
amplitude



radial offset
(random direction)

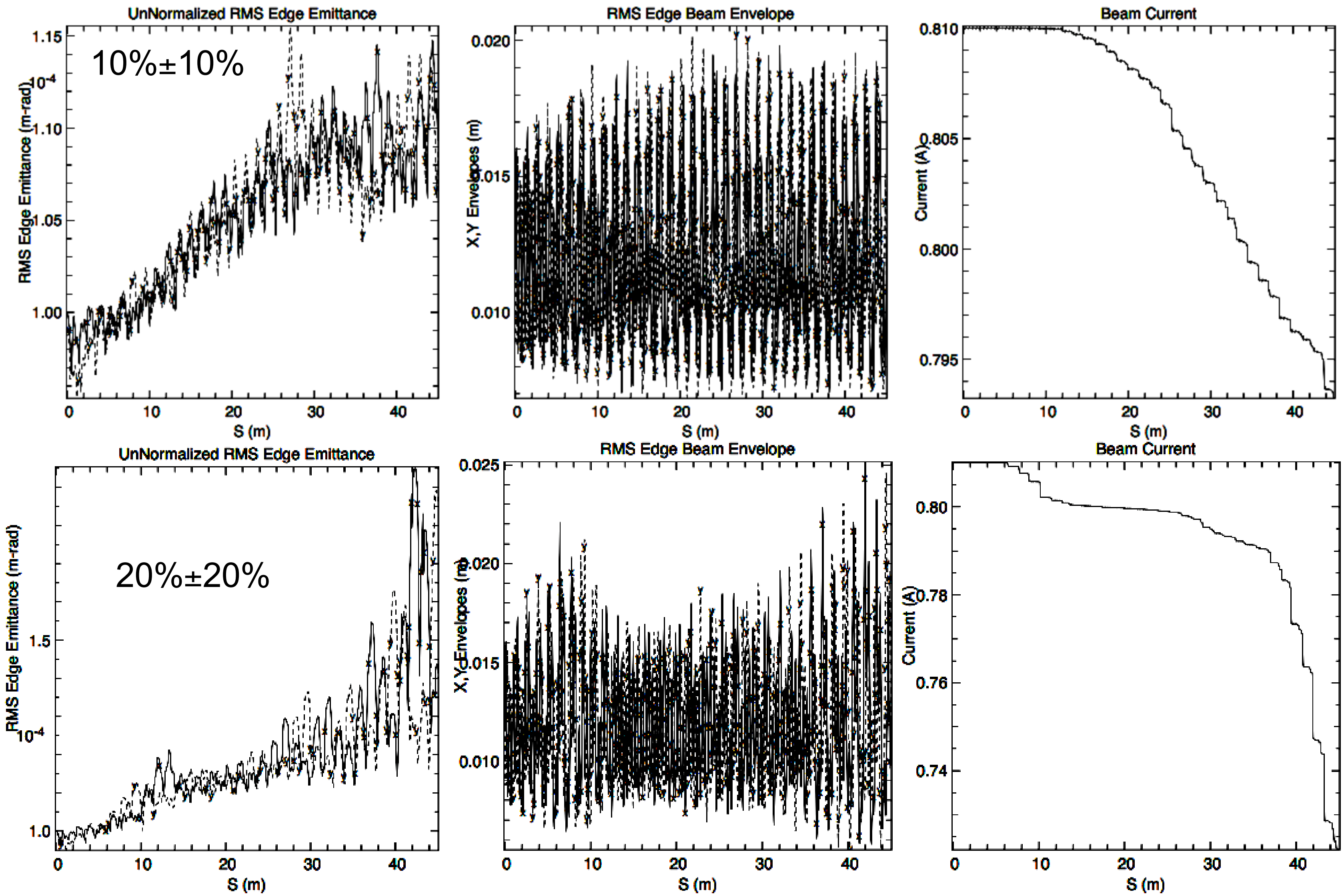


radial shape variation

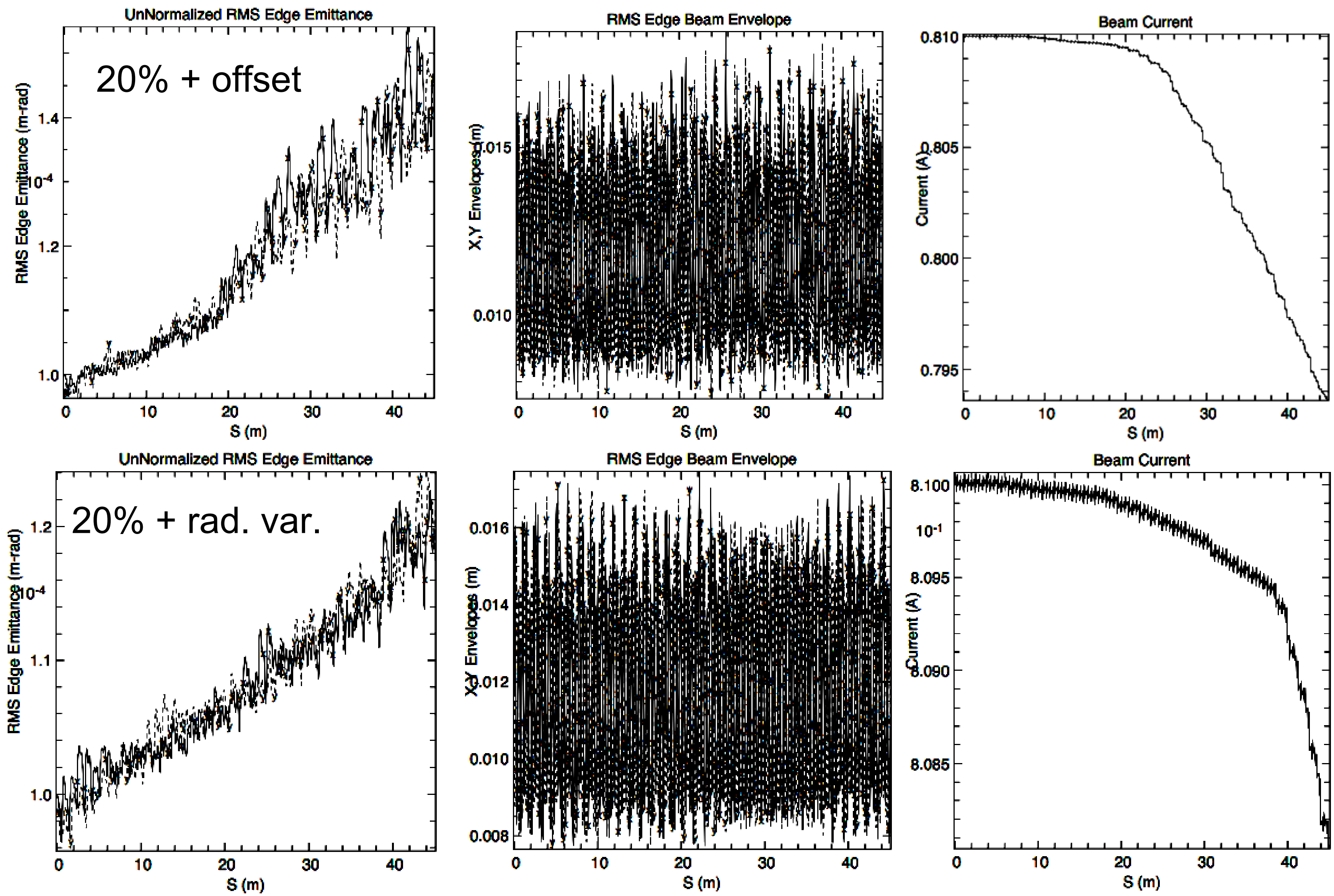


ramp (rotating)

Electron effects on ions: Emittance, envelope grow gradually until envelope reaches pipe wall (r = 2.3 cm)

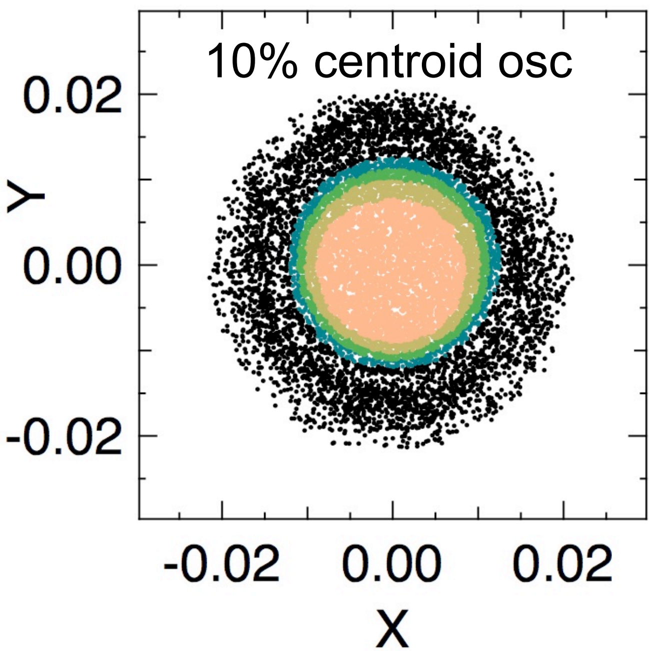


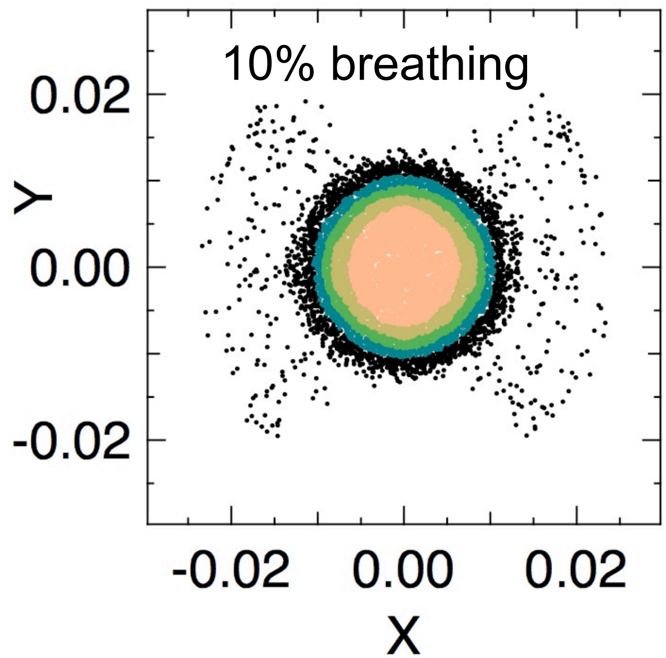
Emittance, envelope, current for random offset runs



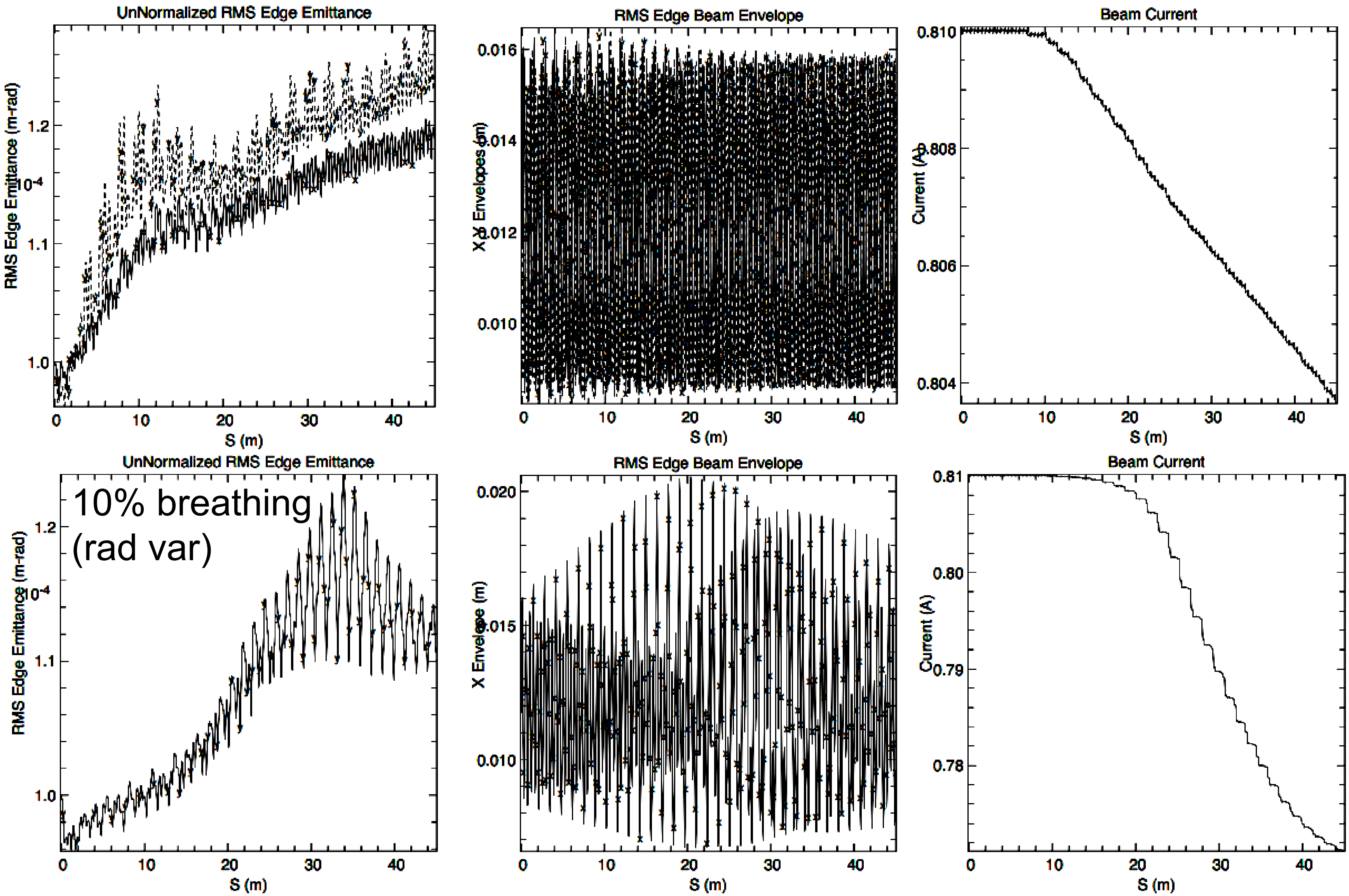
E-cloud effects more potent if resonant with breathing

- Performed a series of runs which attempt to couple to natural modes of the beam
  - Centroid oscillation (via rotating ramp in density): weak effect
  - Breathing (via periodic change of radial shape of e-cloud))
    - For most resonant case, get effects comparable to random amplitude variation with about half the n_e (and recall that for random variations, centroid displacement and radial shape variation were less effective than amplitude variation)





Resonant e-cloud effects on beam quality



Options for bridging electron and ion timescales

- Challenge: be able to simulate electrons and ions simultaneously, and to account for electrons moving from regions of strong **B** to weak/no **B**.
- Options
  - Drift (or gyro-) kinetics in quads, full kinetics in gaps, with discontinuous transition (implementation in progress)
  - Update **v**, **x** using Boris mover without tanh correction (Parker & Birdsall, JCP '91: recover correct drifts in simple test cases)
  - Interpolate between drift (gyro) and full kinetics
    - Relax on d**v**/dt

$$\frac{d\mathbf{v}}{dt} = \mathbf{b}\cdot e\mathbf{E} - \frac{\alpha}{\tau}\left(\mathbf{v}_\perp - \mathbf{v}_d\right) + \left(1-\alpha\right)\left(\frac{d\mathbf{v}_\perp}{dt}\right)_{Lorentz}$$

    - Relax on $\mathbf{v}_\perp$

$$\tilde{\mathbf{v}} = \mathbf{v}_{old} + \Delta t\left(\frac{d\mathbf{v}}{dt}\right)_{Lorentz}$$

$$\mathbf{v}_{new} = \mathbf{bb}\cdot\tilde{\mathbf{v}} + \alpha\mathbf{v}_d + (1-\alpha)\tilde{\mathbf{v}}_\perp$$

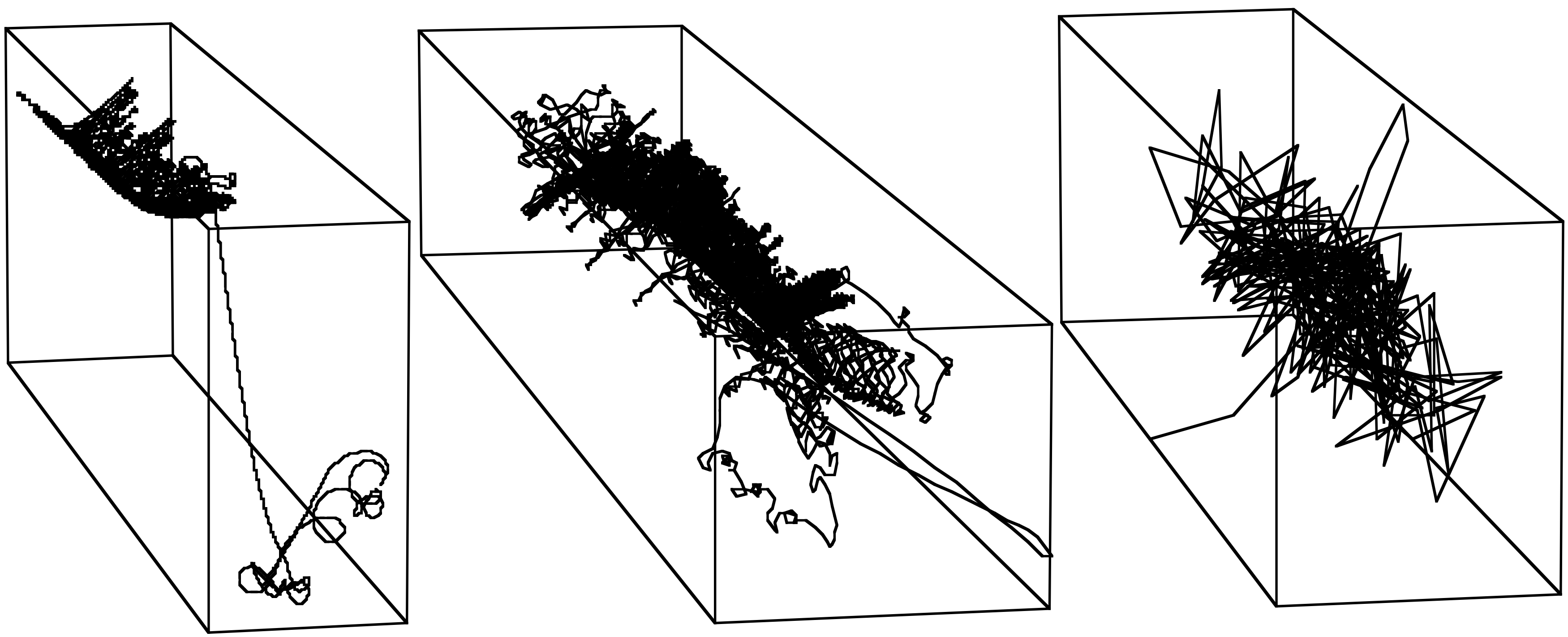
with α an interpolation function, e.g. $\exp[-1/(\omega_c \Delta t)^p]$

Bridging timescales (cont)

- Issues/notes
  - Long-timestep Boris doesn't work well; see next slides
  - The two interpolation schemes
    - Need to use in field-free as well as high-field regions precludes parallel step along pre-computed field lines, so timestep must be small enough that parallel motion accurately follows **B**
    - Either scheme can be centered; 1st simpler but accuracy/stability questions
  - Framework to accommodate any of the hybrid schemes partially implemented in WARP.

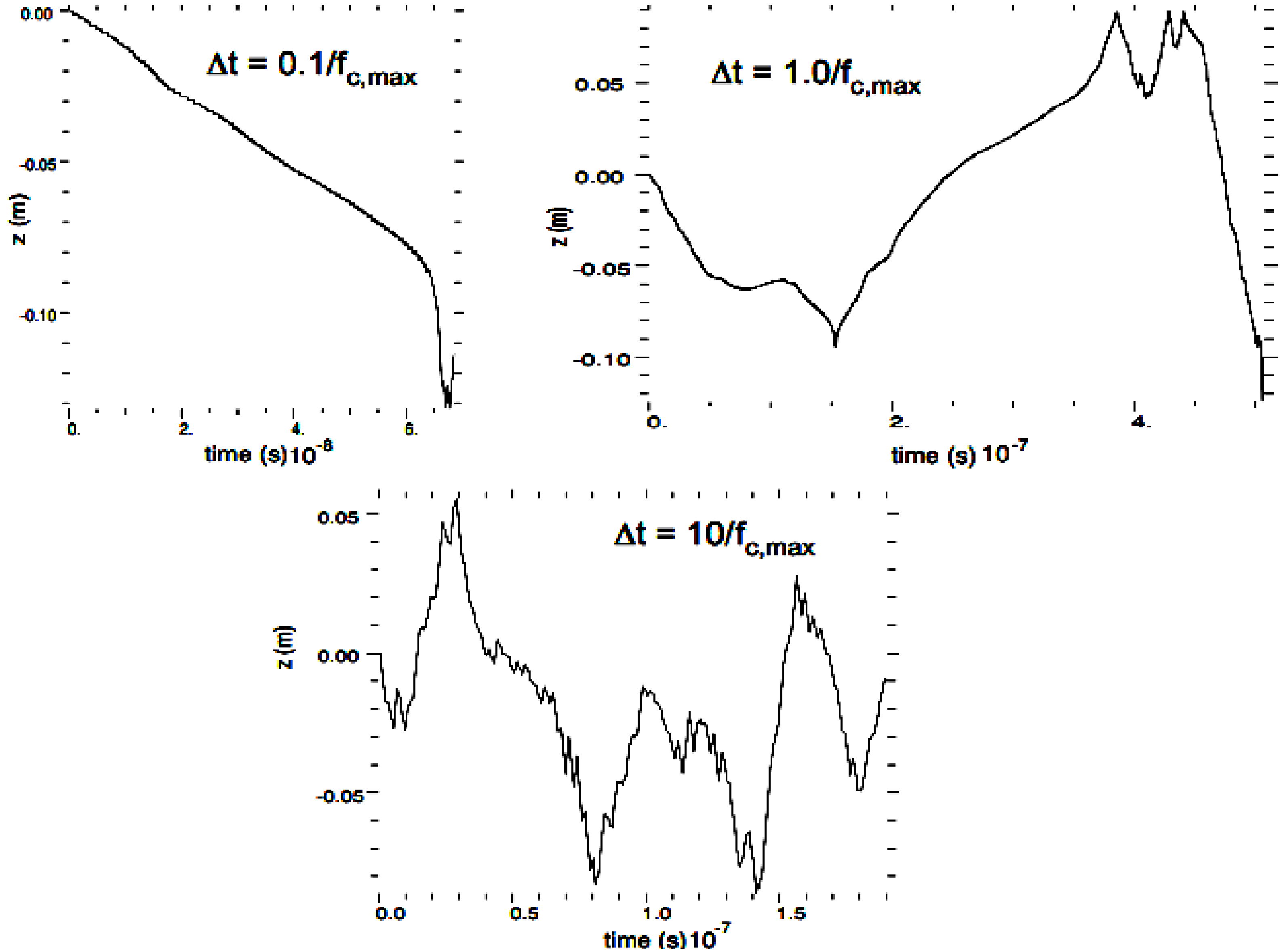
Large-timestep Boris mover not a good solution

ELECTRON ORBITS VS STEP SIZE



$\Delta t = 0.1/f_{c,max}$ $\Delta t = 1.0/f_{c,max}$ $\Delta t = 10/f_{c,max}$

Large-timestep Boris mover not a good solution (cont)



“Merging” WARP and POSINST

- WARP: main Particle-In-Cell accelerator for HIF
  - 3-D electrostatic, complex geometries, F90+python
- POSINST: LBNL’s Center for Beam Physics code for ECE
  - 2-D electrostatic, ECE routines, rudimentary geometry, F77
- WARP needs ECE module; POSINST needs 3-D+geometry
- Strategy: share modules and communicate
- POSINST was modified
  - SEY module was extracted and packaged in stand-alone library (SBIR collaboration with Tech-X – see poster RP1-080)
  - F77 COMMON translated to F90 MODULES
  - Uses Python wrapper from D.P. Grote
- Status: WARP and POSINST use same SEY library and communicate though Python interface

Summary/conclusions

- High current, fill factor, pulse length, unclean walls of HIF induction accelerators dominant electron sources are ionization of neutrals released from walls
  - except ion-produced secondary electrons for short pulse expts or after drift compression
- Developing self-consistent modeling capability for e-cloud formation, dynamics, effects on ions
- Simulation of dynamics of secondary electrons from ion first and second impacts shows
  - n_e concentrated near edges about principal axes (due to **B**)
  - importance of adding ion scattering at walls
  - significance of nonadiabatic trapping
- Simulation of ion evolution with various model electron distributions shows:
  - effect of random amplitude variations > random offsets > const n_e
  - gradual growth of emittance & envelope, small current loss, until envelope reaches wall
  - Faster-than linear scaling with n_e
  - Perturbations resonant with breathing oscillations more effective than random variations (and not so for centroid oscillations)

Summary (cont)

- Progressing toward a self-consistent simulation capability:
  - Merging capabilities of POSINST (ecloud sources for HEP applications) with WARP
  - Runs presented which follow lost ions and calculate electron cloud including real dynamics in quadrupole fields
  - Options for bridging disparate electron and ion timescales under exploration
    - Simplest option (long-timescale Boris mover) appears inadequate.
    - Hybrid drift/full-kinetic mover partially implemented in WARP